

Z-INTERCONNECTIONS WITH LIQUID CRYSTAL POLYMER DIELECTRIC FILMS

1. Technical Field

The present invention relates generally to multilayered laminates, and more particularly
5 to multilayered laminates with dielectric layers that include liquid crystal polymer (LCP)
dielectric material.

2. Related Art

Organic substrates comprising multilayer laminates have been and continue to be
developed for many applications. However, it would be desirable to reduce costs and
10 inefficiencies that currently characterize fabrication of multilayer laminates.

Summary of the Invention

The present invention provides a multilayered stack, comprising:
a first dielectric layer that includes a first liquid crystal polymer (LCP) dielectric material,
wherein a first electrical circuitization is on and in direct mechanical contact with a surface of the
15 first dielectric layer; and
a second dielectric layer that includes a second LCP dielectric material, wherein a first
electrically conductive plug includes a first electrically conductive material and extends through
a thickness of the second dielectric layer, wherein a second electrical circuitization is on and in
direct mechanical contact with a surface of the second dielectric layer, wherein the second

electrical circuitization is in direct mechanical and electrical contact with a first end of the first electrically conductive plug, wherein the second dielectric layer is directly bonded to the first dielectric layer with no extrinsic adhesive material bonding the second dielectric layer to the first dielectric layer, wherein the second dielectric layer is directly bonded to the first electrical circuitization with no extrinsic adhesive material bonding the second dielectric layer to the first electrical circuitization, and wherein the first electrically conductive plug is fluxlessly soldered to the first electrical circuitization.

The present invention provides method for forming a multilayered stack, comprising the steps of:

- 10 forming a first dielectric layer that includes a first liquid crystal polymer (LCP) dielectric material, wherein a first electrical circuitization is on and in direct mechanical contact with a surface of the first dielectric layer;
- 15 forming a second dielectric layer that includes a second LCP dielectric material, wherein a first electrically conductive plug includes a first electrically conductive material and extends through a thickness of the second dielectric layer, wherein a second electrical circuitization is on and in direct mechanical contact with a surface of the second dielectric layer, wherein the second electrical circuitization is in direct mechanical and electrical contact with a first end of the first electrically conductive plug;
- 20 fluxlessly soldering the first electrically conductive plug to the first electrical circuitization; and

subjecting the first dielectric layer, the second dielectric layer, and the first electrical circuitization to a temperature less than the lowest nematic-to-isotropic transition temperature of the first and second LCP dielectric materials, for a dwell time and at an elevated pressure that is sufficient to cause the first and second LCP dielectric materials to plastically deform and directly bond the second dielectric layer to the first dielectric layer and directly bond the second dielectric layer to the first electrical circuitization with no extrinsic adhesive material disposed between the second dielectric layer and the first dielectric layer and with no extrinsic adhesive material disposed between the second dielectric layer and the first electrical circuitization.

10 The present invention advantageously reduces processing time and processing costs in the fabrication of multilayer laminates.

Brief Description of the Drawings

15 FIG. 1 depicts a localized molecular domain in the liquid crystal phase of a liquid crystal polymer (LCP) dielectric, with directional ordering of polymer chains, in accordance with embodiments of the present invention.

FIG. 2 depicts a localized molecular domain in the isotropic phase of a LCP dielectric, with little or no directional ordering of polymer chains, in accordance with embodiments of the present invention.

20 FIGS. 3 and 4 illustrate flat-bed press lamination for lamination of stacked layers that include LCP dielectric material, in accordance with embodiments of the present invention.

FIG. 5 illustrates an autoclave lamination press for lamination of stacked layers that include LCP dielectric material, in accordance with embodiments of the present invention.

FIG. 6 depicts an electrical structure having a double-sided cladded laminate with first and second electrically conductive layers respectively positioned on opposite surfaces of a dielectric layer, in accordance with embodiments of the present invention.

FIG. 7 depicts the electrical structure of FIG. 6 after a removable protective coating has been applied to the first electrically conductive layer, in accordance with embodiments of the present invention.

FIG. 8 depicts the electrical structure of FIG. 7 after removal of the second electrically conductive layer, in accordance with embodiments of the present invention.

FIG. 9 depicts an electrical structure having a single-sided cladded laminate with an electrically conductive layer positioned on a surface of a dielectric layer, in accordance with embodiments of the present invention.

FIG. 10 depicts the electrical structure of FIG. 9 after a protective coating has been applied to the electrically conductive layer, in accordance with embodiments of the present invention.

FIG. 11 depicts the electrical structure of FIG. 8 or FIG. 10 after formation of vias in the dielectric layer, in accordance with embodiments of the present invention.

FIG. 12 depicts the electrical structure of FIG. 11 after the vias have been filled with an electrically conductive material to form electrically conductive plugs in the vias, in accordance with embodiments of the present invention.

FIG. 13 depicts the electrical structure of FIG. 12 after an electrically conductive cap has been formed on the electrically conductive plugs, in accordance with embodiments of the present invention.

FIG. 14 depicts the electrical structure of FIG. 13 after removal of the protective layer, and after a photoresist has been patterned, exposed, and developed after being applied to the copper foil, in accordance with embodiments of the present invention.

FIG. 15 depicts the electrical structure of FIG. 14 after the copper foil has been circuitized in accordance with the photoresist pattern, and after the photoresist has been removed to form a circuitized layer, in accordance with embodiments of the present invention.

FIG. 16 depicts the electrical structure (i.e., circuitized layer) of FIG. 15 immersed in a plating solution, in accordance with embodiments of the present invention.

FIG. 17 depicts the electrical structure (i.e., circuitized layer) of FIG. 15 being treated with a plasma such as a fluorinated plasma gas, in accordance with embodiments of the present invention.

FIG. 18 depicts multiple circuitized layers stacked and aligned to form a multilayered stack with Z-axis interconnections, in accordance with embodiments of the present invention.

FIG. 19 depicts the multilayered stack of FIG. 18 after the circuits on adjacent layers have been electrically joined by soldering leaving void volumes in the multilayered stack, in accordance with embodiments of the present invention.

FIG. 20 depicts the multilayered stack of FIG. 19 after resin has been infused into the void volumes and subsequently cured.

FIG. 21 depicts the multilayered stack of FIG. 19 with the dielectric layers comprising a liquid crystal polymer (LCP) material and after high pressure has been applied to the multilayered stack to fill the void volumes with the LCP material and bond dielectric layers of adjacent circuitized layers with each other, in accordance with embodiments of the present invention.

Detailed Description of the Invention

Liquid crystal polymer (LCP) dielectric materials have many positive attributes for forming dielectric layers, including good dielectric properties, low cost, and good mechanical properties. LCP dielectric materials have some characteristics similar to those of polyimides, such as good tear resistance and good stretching resistance, which make LCP dielectric materials suitable for processing (e.g., circuitizing, plating, etc.) in very thin layers. LCP films may offer advantages over polyimide films such as better electrical properties, better moisture resistance, better dimensional stability, and lower cost. However, to form multilayer structures with either LCP or polyimide films generally requires the use of adhesive dielectric films. The present invention discloses how to cause LCP dielectric material to adhere to a layer of material (e.g., a metal layer or a dielectric layer) without need for an extrinsic intervening adhesive layer, which reduces layer thickness, processing costs, and material costs. In addition, LCP dielectric films of this type are flame retardant without the use of halogen based additives. Multilayer composites made with these dielectrics may also be flame retardant without the use of halogens.

A commercially available LCP dielectric material that may be used in conjunction with

the present invention is the BIAC thermotropic liquid crystal polymers which exhibit thermoplastic behavior and are manufactured in sheet or roll form by W.L. Gore & Associates, Inc. Information on the BIAC liquid crystal polymers may be obtained at the web site: <http://www.gore.com/electronics>. Another commercially available LCP dielectric material that 5 may be used in conjunction with the present invention is the ZYVEX LCP thermotropic liquid crystal polymers which exhibit thermoplastic behavior and are manufactured in roll form by the Rogers Corporation. Generally, any LCP dielectric material is potentially usable with the present invention, depending on the material properties desired in a given application.

United States Patent 6,274,242 (Onodera et al. 2001) ("Onodera '242"), hereby 10 incorporated by reference in its entirety, discloses a method of making LCP films which include well known thermotropic liquid crystal polyester and thermotropic liquid crystal polyester amide. Said LCP films are prepared from four classes of compounds identified in Tables 1-4 of Onodera '242. Examples of resultant LCP structural units derived from the four classes of compounds are illustrated in Table 5 of Onodera '242. The LCP dielectrics disclosed in Onodera '242 are 15 merely exemplary, and many other LCP dielectrics are within the scope of the present invention. Generally, any method known to one of ordinary skill in the art may be used to make the LCP dielectric material.

A LCP dielectric may exist in one of three phases: a liquid crystal phase (e.g., nematic, smectic, cholesteric), an isotropic phase, and a chemically unstable phase, which respectively 20 correspond to three temperature domains, namely a liquid crystal temperature domain, an isotropic temperature domain, and a chemically unstable temperature domain.

In the liquid crystal phase or liquid crystal temperature domain, localized molecular regions or domains of the LCP dielectric comprise polymer chains which are directionally ordered (i.e., anisotropically distributed) such as by processing. In the liquid crystal phase, different localized molecular domains may have different directional ordering, and many 5 localized molecular domains may have little or no directional ordering. These polymer chains are typically less than fully rigid. Such a localized molecular domain having directional ordering may include domains of molecules and/or groups of adjacent molecules, such that the spatial extent of the localized molecular domain is of the order of a thousand or hundreds of angstroms or less. Macroscopic material properties of the LCP dielectric (e.g., coefficient of thermal 10 expansion (CTE), dielectric constant, thermal conductivity, etc.) are sensitive to the directional order in the localized molecular regions, and material properties of LCP dielectric materials are anisotropic in accordance with the directional ordering. The macroscopic material properties of the LCP dielectric are also dependent on the shape, size, shape distribution, and size distribution of the localized molecular regions.

15 The LCP dielectric material is manufactured by techniques known to one of ordinary skill in the art to produce a directional ordering that provides the desired material properties in the liquid crystal phase. Such techniques may include, *inter alia*, two-dimensional shear imparted to the LCP dielectric material through film extrusion or through stretching in the roll direction and stretching in the direction normal to the roll direction, as the LCP dielectric 20 material is being unrolled at a prescribed temperature and velocity. The shear may alternatively be imparted by strong polarizing electric fields.

The LCP dielectric material remains in the liquid crystal phase if its temperature is in the liquid crystal temperature range; i.e., below a temperature called the nematic-to-isotropic transition temperature (T_{NI}). Thus, T_{NI} represents the transition from the liquid crystal phase to the isotropic phase of a LCP dielectric material. The numerical value of T_{NI} depends on the specific LCP dielectric material being utilized. Additionally, the directional ordering and consequent macroscopic material properties of the LCP dielectric material are essentially invariant to changes in temperature provided that the temperature remains within the liquid crystal temperature range and does not depart from the liquid crystal temperature range.

Macroscopic material properties are preserved as temperature is varied within the liquid crystal temperature domain, because there is insufficient thermal energy in the liquid crystal phase to reorient the directionality of polymer chains of the LCP dielectric material (i.e., to overcome the inter-molecular attractive forces).

The LCP dielectric material plastically deforms when subject to high pressure in the liquid crystal phase. For example, in the manufacturing of chip carriers, the high pressure may result from a combination of applied normal pressure and local geometrical irregularities such as stress concentrations resulting from surface roughness, signal lines, vias, etc. Thus if the LCP dielectric material is laminated to a layer of material (comprising dielectric, metal, etc.) at high pressure and at elevated temperature within the liquid crystal phase, then the LCP dielectric material will plastically deform and conform to the macroscopic geometry of the surface and surface features (e.g., vias) of the layer of material. This capability of the LCP dielectric material to plastically conform, under sufficient pressurization while in the liquid crystal phase during the

dwell time, to the surface and surface features of an adjacent layer is an unexpected result determined through experimentation by the inventors of the present invention, and serves as a foundational basis for the present invention. With the present invention, LCP dielectric material may be laminated to an adjacent surface of a layer of material through elevation of temperature 5 within the liquid crystal temperature domain, and under sufficient pressurization to induce plastic deformation and consequent adhesion to the adjacent surface, while preserving its macroscopic material properties. This process of plastic adhesion does not require the presence of an extrinsic adhesive layer to bond the LCP dielectric material to the adjacent layer.

FIG. 1 depicts a localized molecular domain **200** in the nematic type liquid crystal phase 10 with directional ordering of polymer chains, in accordance with embodiments of the present invention. The domain **200** includes polymer chains **201-208** ordered directionally such that the average directional orientation, angularly integrated over the directional orientations of the polymer chains **201-208**, is approximately in the direction **210**. Such angular integration may be performed in various ways as is known to one of ordinary skill in the art (e.g., different 15 components of a given polymer chain may be weighted differently in the angular integration). Regardless of this specific definition used to define the angular average, however, the angular distribution of the directional orientations is clearly anisotropic such that there is a preferred direction at or near the direction **210**.

In this illustration, each of polymer chains **201-208** is shown as a linear chain of 20 alternating rigid and semi-flexible components. For example, polymer chain **204** comprises the sequence of polymer components **221-226**, wherein components **221**, **223**, and **225** are rigid

components, and wherein components 222, 224, and 226 are semi-flexible components. An example of a rigid component is a polymer having a polymer backbone that includes repeating units of substituted aromatic rings (e.g., benzene, biphenyl, naphthalene, etc.) such as disclosed in U.S. Patent 6,274,242 (Onodera et al, see Tables 1, 2, 3, 4, and 5) and U.S. Patent 5,900,292 (5 Moriya, see formulae 1, 2, 3, and 4). The rigid component may have reactive functional groups (e.g., hydroxy, amine, cyanate, carboxylic acid, and combinations thereof, etc.). An example of a semi-flexible component is a polymer having a polymer backbone that includes repeating units such as aliphatic segments (e.g., oxymethylene units, oxyethylene units, vinyl ether units, siloxanes units, etc.). The semi-flexible component may have chemically functional groups (e.g., 10 hydroxy, amine, cyanate, carboxylic acid, and combinations thereof, etc.). Such a polymer may be prepared in two ways. First, the ends of adjacent rigid and semi-flexible components may be chemically coupled to each other to form esters, ethers, amides, etc. links in the polymer chain. Second, the ends of adjacent rigid components may be chemically coupled to each other to form ester, ether, amides (etc.) links in the polymer chain. In this second case, the links or 15 connecting segments (esters, ethers, amides, etc.) would be the only semi-flexible component.

While FIG. 1 shows polymer chains 201-208 as each being a linear chain of alternating rigid and semi-flexible components, any linear chain of rigid and semi-flexible components (e.g., a non-alternating sequence of rigid and semi-flexible components) is within the scope of a localized molecular domain. While FIG. 1, shows polymer chains 201-208 as each being a linear 20 chain of components, any polymer chain topography is within the scope of a localized molecular domain. For example, a localized molecular domain may also or alternatively include a chain

structure that comprises one or more side chains linked to a linear chain. While FIG. 1, shows a two-dimensional representation of linear chains, the localized molecular domain generally has chain structures which are oriented in three-dimensional space. For example, portions of any of the polymer chains **201-208** may extend above or below the depicted plane shown in FIG. 1.

5 Accordingly, FIG. 1 may be viewed as a projection of a three-dimensional localized molecular domain onto a two-dimensional surface and the chains pictured may continue above and below the depicted plane.

In the isotropic phase or isotropic temperature domain, which exists at temperatures at or above the nematic-to-isotropic transition temperature (T_{NI}), there is sufficient available thermal energy to permit molecular diffusion and motion to change the directional ordering within the LCP dielectric. Thus as temperature changes from below T_{NI} to above T_{NI} , there is a loss of directional order and the directional orientations become more random. As a consequence, macroscopic material properties will generally change in the temperature transition from below T_{NI} to above T_{NI} , since the macroscopic material properties are sensitive to direction orientations 10 of polymer chains in the LCP dielectric material, as described *supra*. When lamination of LCP dielectric material to a layer of material is performed at a temperature in the isotropic temperature range, the LCP dielectric material softens and liquefies and thus flows into the macroscopic geometry of the surface and surface features of the layer of material. Upon 15 subsequent cooling its thermal history and processed-in directional order is changed. In contrast, when lamination of LCP dielectric material to a layer of material is performed at a temperature in the liquid crystal temperature range with sufficient pressurization, the LCP dielectric material 20

does not flow but rather plastically deforms into the macroscopic geometry of the surface and surface features of the layer of material, as explained *supra*. The present invention teaches lamination of LCP dielectric material to a layer of material only at a temperature in the liquid crystal temperature range and thus teaches an invention that preserves macroscopic material properties during the laminating process. The lower temperature in the liquid crystal temperature range prevents any risk of the material melting or of domain re-orientation of large regions. An additional advantage is that no extrinsic adhesive layer is needed to bond the LCP dielectric material to the layer of material.

FIG. 2 depicts a localized molecular domain **250** in the isotropic phase in which there is little or no directional ordering of polymer chains, in accordance with embodiments of the present invention. The domain **250** includes polymer chains **251-260** ordered directionally such that the average directional orientation, angularly integrated over the directional orientations of the polymer chains **251-260**, is approximately “zero”; i.e., there is essentially no preferred angular orientation or direction associated with the domain **250**.

Each of polymer chains **251-260** is shown as a linear chain of alternating rigid and semi-flexible components. For example polymer chain **259** comprises the sequence of polymer components **271-277**, wherein components **271**, **273**, **275**, and **277** are semi-flexible components, and wherein components **272**, **274**, and **276** are rigid components. The rigid and semi-flexible components in the polymer chains of FIG. 2 are respectively analogous to the rigid and semi-flexible components in the polymer chains of FIG. 1, and the examples of rigid and semi-flexible polymer components discussed *supra* in conjunction with FIG. 1 likewise apply to the rigid and

semi-flexible components of FIG. 2.

While FIG. 2 shows polymer chains **251-260** as each being a linear chain of alternating rigid and semi-flexible components, any linear chain of rigid and semi-flexible components (e.g., a non-alternating sequence of rigid and semi-flexible components) is within the scope of a

5 localized molecular domain. While FIG. 2, shows polymer chains **251-260** as each being a linear chain of components, any polymer chain topography is within the scope of a localized molecular domain. For example, a localized molecular domain may also or alternatively include a chain structure that comprises one or more side chains linked to a linear chain. While FIG. 2, shows a two-dimensional representation of linear chains, the localized molecular domain generally has
10 chain structures which are oriented in three-dimensional space. For example, portions of any of the polymer chains **251-260** may extend above or below the depicted plane shown in FIG. 2. Accordingly, FIG. 2 may be viewed as a projection of a three-dimensional localized molecular domain onto a two-dimensional surface and the chains pictured may continue above and below the depicted plane.

15 In the chemically unstable phase or chemically unstable temperature domain, which occurs at significantly higher temperatures than the nematic-to-isotropic transition temperature (T_{NI}), there is sufficient available thermal energy to cause chemical decomposition within the LCP dielectric. The chemically unstable phase is not relevant to the present invention.

The present invention discloses a method for bonding LCP dielectric material to a layer
20 of material (e.g., a dielectric layer or a metal layer or a combination thereof). As background for the present invention, the following discussion describes tests performed by the inventors of the

present invention. In tests dating to 1994, the present inventors have attempted melt processing of LCPs, as known and taught in the art, to build multi-layer structures, with the approach of using precise temperature control to laminate the materials at temperatures just above or just below the "melting" temperature (i.e., T_{NI}) as determined by differential scanning calorimetry and by parallel plate rheometry. These experiments are characterized by inconsistent results in adhesion, laminate thickness, edge squeeze out, and importantly the physical properties of resulting laminate. Of particular note are the inconsistent changes that occurred in the coefficient of thermal expansion. This is a clear indication that the properties of the base laminate have been changed, essentially destroying their utility for the use intended, and therefore requiring the use of adhesive layers to form multi-layer circuits.

In contrast, experiments performed during June through September of 2002 have shown that by lowering the temperature to below T_{NI} , consistent adhesion is achieved without altering the properties of the base laminate. For example, Gore BIAC material, having a 2 mil thickness with 15 um of copper cladding on each side, was utilized. Etching away the copper, the inventors determined that the coefficient of thermal expansion (CTE) was approximately 20 to 25 ppm/ $^{\circ}$ C as received from the vendor. A thermal mechanical analyser was used to determine the CTE in various locations on a panel that measured approximately 13 x 18 inches. The CTE was measured in both x-coordinate and y-coordinate directions (i.e., in the two directions that are perpendicular to the thickness direction of the BIAC layer and also perpendicular to each other). Both a film-fiber configuration and a more conventional contacting probe were used to make these measurements.

After characterizing the properties of individual plies of the LCP, multi-ply laminates were prepared. The laminates comprised 4 ply and 6 ply thick composites formed using the Gore BIAC material, from which the copper cladding had been etched away. The parts were subjected to a lamination process that involved heating to 560 °F at a heatup rate of 15 °F per minute, next 5 followed by a dwell time of approximately 20 to 30 minutes, and then followed by cooling at approximately 20 °F per minute to room temperature. Dwell time is defined herein, including in the claims, as a time interval during which the part being laminated is subjected to the highest temperature (within a reasonable temperature tolerance of said highest temperature due to statistical scatter and other minor variations) that the part experiences during the entire 10 lamination process, said entire lamination process including all processing steps. Note that the maximum temperature of 560 °F is less than the liquid crystal transition temperature (assumed herein to be essentially the same as T_{NL}) of 635 °F of the Gore BIAC material. The lamination was accomplished using a flat bed press with electrically heated steel platens. The pressure was maintained at 2500 psi throughout the processing. Stainless steel planishing plates and copper 15 release sheets were employed, as well as interleaving layers of polytetrafluoroethylene (PTFE) and copper to make a press pad above and below the tooling. Upon removal from the press, the inventors found no evidence of dielectric squeeze out at the edges of the laminate.

The thermal mechanical analysis was repeated and determined that the x-coordinate and y-coordinate (in-plane) CTE were unaltered by the lamination process. Adhesion tests were 20 performed, using a 180 degree pull at 1 inch per minute, and an inner layer adhesion strength in excess of 6 lbf/inch was determined.

The same lamination process was repeated to evaluate the extent to which topography associated with realistic circuit features could be accommodated. A layer of Roger 2800 dielectric (PTFE/SiO₂ filler) was used, and the layer of Roger 2800 dielectric had surface features including 12 μm thick Cu formed into the circuit line of 30 to 50 μm in width. The layer of the Gore BIAC LCP (50 μm thick) was positioned above the Roger 2800 dielectric surface and the lamination was performed at the previously described conditions. Upon removal and subsequent cross sectioning, it was found that the circuit features were completely encapsulated. As before, there was no edge squeeze out. Adhesion testing showed an inner layer adhesion strength in excess of 4 lbf/inch between the LCP and Roger 2800 dielectric.

In another experiment, standard photolithography techniques were applied to copper clad LCP (i.e., 15 μm copper cladded to Gore BIAC LCP) to form a pattern of clearance holes ranging from 50 to 500 μm diameter on one of the copper surfaces. A second sheet of Gore BIAC LCP (with copper removed) was placed against the side of the first sheet that had the clearance holes. After repeating the lamination process as described *supra*, the part was cross-sectioned and it was determined that the holes were completely filled with BIAC LCP dielectric material. Again there was no evidence of edge squeeze out, and the adhesion was consistent across the panel.

The lamination experiments were first performed in panel sizes as small as 4" x 4" in an electrically heated 75 ton laboratory press with no vacuum enclosure, manufactured by PHI Corporation. The results were duplicated in an electrically heated 125 ton Wabash press with a vacuum enclosure, and finally in a 600 ton electrically heated TMP press in 13" x 18" format. These larger samples were used to establish the uniformity of adhesion, hole fill, and physical

properties over a panel size that would be practical in manufacturing.

Based on the preceding experiments and supplementary analysis, which are consistent with the model (described *supra*) of directional ordering characteristics of LCP dielectric materials as being differentiated in the liquid crystal and isotropic phases, the basic technique of the present invention for laminating a LCP dielectric material to a layer of material (e.g., a dielectric layer or a metal layer or a combination thereof) is to perform the lamination at a temperature T wholly in the liquid crystal temperature range (i.e., $T < T_{NI}$) with no excursion into the isotropic temperature range, under sufficient pressurization and for a sufficient time to cause the LCP dielectric material to be effectively laminated to the layer of material,

For the Gore BIAC LCP material, T_{NI} is about 635 °F. For the Gore BIAC LCP material, the maximum lamination temperature should be less than 635 °F; however, due to temperature uncertainties and spatial variation, a maximum processing temperature for lamination may be about 620 °F, and representative lamination temperature ranges include, *inter alia*, 540 °F to 620 °F and 545 °F to 580 °F. For the Rogers ZYVEX LCP material, T_{NI} is about 536 °F. For the Rogers ZYVEX LCP material, the maximum lamination temperature should be less than 536 °F; however, due to temperature uncertainties and spatial variation, a maximum processing temperature for lamination may be about 520 °F, and representative lamination temperature ranges include, *inter alia*, 440 °F to 520 °F and 465 °F to 490 °F.

Although the preceding experiments were performed at a pressure of 2500 psi, the present inventors have used pressure in the range of 1000 to 3000 psi and achieved good adhesion. It was found that an improvement in uniformity correlated with increasing pressure. The

effectiveness of the pressure depends on the aspect ratio of the features that must be filled during the lamination. The testing performed by the inventors thus far indicate that a range in pressure of 2000 to 2500 psi is particularly effective, as well as practical and economical for use in a conventional manufacturing environment. Extreme pressures can have the drawback of

5 shortened life for the tooling and platens, and also require increased capacity for the press itself.

The dwell times used by the present inventors include keeping the material LCP dielectric pressurized at maximum temperature for durations as short as 2 to 5 minutes to durations as long as 60 minutes. It was found that no undesirable "edge squeeze out" or other evidence of excess flow occurs with the longer times, although some improvement in adhesion uniformity

10 may result. Thus the maximum dwell time for temperature and pressure should generally be at least 2 minutes, and applicable ranges of dwell times include, *inter alia*, 2 to 60 minutes and 15 to 30 minutes. A minimum dwell is required to ensure temperature uniformity. However, the quality of the filling of features should improve with increasing dwell time. On the other hand, shorter times are favorable for economy of manufacturing, and the shorter dwell times reflect this

15 goal of economy. Nonetheless, no upper limit of dwell time has been observed by virtue of the resulting properties of the laminates.

Repeating the lamination cycle twice may improve the uniformity of adhesion, and by repositioning the product in the lamination press (perhaps turning it 180 degrees), the low spots become high spots, resulting in more uniform adhesion, especially along the edges.

20 In accordance with the discussion of LCP dielectric materials and the testing relating to lamination of LCP dielectric materials to a layer of material, the LCP material used in the present

invention may be a partially ordered liquid crystal polymer resulting from various processing steps which partially orient the microscopic liquid crystal domains directionally during the manufacturing of the LCP dielectric. Higher order smectic (i.e., orientational and positional order) phases may also be present. Although the preceding discussion focused on homogenous 5 LCP dielectrics, the adhesiveless lamination process of the present invention is also applicable to LCP materials that contain fillers, such as ceramic or organic, particulate or fiber-like, or even metallic particles. Further, expanded PTFE as a reinforcement in LCP materials is within the scope of the present invention.

The desired material properties for the LCP dielectric material, in the context of the 10 present invention, are application dependent. For various applications, material properties may comprise: in-plane CTE (i.e., CTE in direction perpendicular to the thickness direction of a LCP dielectric layer) of about 10 to 25 ppm/ $^{\circ}$ C; dielectric constant of about 2.5 to 3.0; Young's modulus of about 3 to 6 GPa; dissipation factor of less than about 0.003; and moisture absorption of less than about 0.2% for 96 hours at 121 $^{\circ}$ C and 2 atm. The thickness of the LCP dielectric 15 layers can vary according to the desired design performance characteristics of the multi-layered interconnect structure, and said thicknesses may be about equal if so dictated by design performance requirements. For manufacturing efficiency, lamination is typically performed with a "book" that includes multiple pages.

The following discussion discloses two practical methods of performing lamination of a 20 multi-layered interconnect structure (called a "page"), namely flat-bed press lamination (see FIGS. 3-4) and autoclave lamination (see FIG. 5).

FIGS. 3 and 4 illustrate flat-bed press lamination for lamination of stacked layers that include LCP dielectric material, in accordance with embodiments of the present invention. In FIG. 3, a flat-bed lamination press 300 is enclosed and structurally supported by a frame 302. FIG. 3 depicts a three-opening flat-bed lamination press 300 that has an upper bolster 304, a middle bolster 308, a lower bolster 306, a top platen 322, mid-platens 324 and 326, a bottom platen 328, books 311-313, guide rods 320, a hydraulic system 329, a vacuum pump 340, and a vacuum feedthru 342. The platens 322, 324, 326, and 328 and books 311-313 may be supported from below by the middle bolster 308 and are constrained from above by the upper bolster 304. The platens 322, 324, 326, and 328 are supported laterally and guided vertically by the guide rods 320. The hydraulic system 329 comprises a hydraulic cylinder 332, hydraulic fluid 334, a piston 330, and a pump (not shown) that circulates the hydraulic fluid 334 by use of a supply line (not shown) that is coupled to the pump. The hydraulic system 329 is used to apply pressure to the platens. Typical operating pressures for the hydraulic fluid 334 are in a range of up to 5000 psi. The pressure applied to the books depends on the relative size of the book versus the diameter of the hydraulic piston 330. With the present invention, pressures in a range of, *inter alia*, about 1000 to about 3000 psi may be applied to the product layers within the books. The chamber of the press may be subject to a vacuum generated by the vacuum pump 340 with the vacuum feedthru 342, so as to minimize oxidation and entrapment of voids during lamination processing. Alternatively, the vacuum pump 340 may be omitted, or turned off and not used during lamination press operation. Not shown are the feedthroughs and supply lines for the platen heating and cooling systems which could be electrically or fluid heated, and fluid cooled.

Book 311 is disposed between top platen 322 and mid-platen 324. Book 312 is disposed between mid-platen 324 and mid-platen 326. Book 313 is disposed between mid-platen 326 and bottom platen 328. While FIG. 3 shows three books 311-313, the flat-bed lamination press 300 may process at least one of such books and as many books as can fit geometrically between the 5 upper bolster 304 and the middle bolster 308, in consideration of the thickness in the direction 310 of the platens and the books. Each of books 311-313 comprises one or more pages, and each page comprises multiple layers and/or multilayered structures to be laminated together by pressurization through movement of the piston 330 in the direction 310 such that each book is compressed between the platens that contact the book on each side of the book (e.g., the book 10 312 is compressed between the platens 324 and 326). The multiple layers and/or multilayered structures of each page comprise one or more LCP dielectric layers. Upon actuation of the press, the piston 330 moves up in the direction 310 and platens 322, 324, 326, and 328 come into contact with books 311-313. The platens that contact the books during the lamination process not only provide surfaces for compressing the books during lamination, but also provide a heat 15 source for elevating the temperature of the LCP dielectric layers in each page of each book as will be explained *infra*.

FIG. 4 shows the detailed structure of book 312 and platens 324 and 326 of FIG. 3, in accordance with embodiments of the present invention. The book 312 comprises an alternating sequence of plate layers and pages between press pads 362 and 364. In particular, the book 312, 20 comprises the alternating sequence of: plate layer 370, page 357, plate layer 380, page 358, and plate layer 390. The plate layer 370 comprises a planishing plate 372 sandwiched between

release sheets 371 and 373. The planishing plate 372 assists in planarizing the page 357.

Various considerations are made in selecting the material of the planishing plate 372, including its thickness, size, and thermal expansion characteristics. In many applications, the planishing plate 372 may comprise stainless steel. The release sheets 371 and 373 should comprise a material (e.g, copper) that enables the plate layer to be easily detached from the page 357 after completion of the lamination processing. The plate layer 380 comprises a planishing plate 382 sandwiched between release sheets 381 and 383, and the planishing plate 382 and release sheets 381 and 383 are respectively analogous to the planishing plate 372 and release sheets 371 and 373. The plate layer 390 comprises a planishing plate 392 sandwiched between release sheets 391 and 393, and the planishing plate 392 and release sheets 391 and 393 are respectively analogous to the planishing plate 372 and release sheets 371 and 373. The press pads 362 and 364 may include a compliant material to give more uniform lamination by compensating for spatial thickness non-uniformities in the pages and release sheets.

Platens 324 and 326 are similarly constructed. In platen 324, heating elements 354 may generate heat in any form that is known to one of ordinary skill in the art such as generation of heat by electrical resistance heaters or by a heated circulating fluid (e.g., oil). Inlet tube 351 and outlet tube 352 are use to circulate fluid (e.g., air, water, etc.) through the platen 324 for cooling purposes. Platen 324 also includes thermocouple ports 353 for using thermocouples to measure platen 324 temperatures. Platen 324 is bounded by wear plates 355 for planarizing the book 312 as the book 312 is pressurized. The wear plates 355 are thermally conductive and transmit heat generated by the heating elements 354 to the book 312. The wear plates 355 should have good

thermal conductivity and may comprise hardened steel in some applications.

FIG. 5 illustrates an autoclave lamination press for lamination of stacked layers that include LCP dielectric material, in accordance with embodiments of the present invention. In FIG. 5, an autoclave 400 comprises a chamber 404 surrounded by an enclosure 402. The 5 chamber 404 comprises a vacuum bag 419 enclosed by flexible membrane 418. A book 410 is placed within the vacuum bag 419. The vacuum bag 419 can have various configurations, but it must completely envelope the book 410, and provide some flexibility so that the vacuum bag 419 will conform to the book 410 upon evacuation (described *infra*). The vacuum bag 419 and the book 410 therewithin are placed in the chamber 404 which is then sealed. The vacuum bag 419 10 may also include a breather ply 409 for the purpose of facilitating complete evacuation of the vacuum bag 419. The vacuum bag 419 with the included book 410 is mechanically supported by a carrier tray 412. The flexible membrane 418 provides a pressure boundary that interfaces with a pressurized, heated gas 420 (e.g., nitrogen) within the portion of the chamber 404 that is exterior to the flexible membrane 418. The pressure differential between the space exterior to 15 the flexible membrane 418 and the space within the vacuum bag 419 may be further controlled by evacuating the air from within the vacuum bag 419 by a vacuum pump 406 via a vacuum supply line 408. The pressurized, heated gas 420 is supplied to the chamber 404 by a source 414 through gas inlet tubing 416. Thus the gas 420 is a medium through which elevated temperature and pressure are applied to book 410 so as to laminate the pages contained within the book 410. 20 The resulting laminations are similar to that achieved in a flat bed lamination press, in that compressive stresses normal to the book 410 are achieved. However, the pressure uniformity is

generally improved by the use of the autoclave 400, since there is an absence of shear tractions on the outer surface of the book 410. Although FIG. 5 shows one vacuum bag 419, the scope of the present invention also includes a plurality of such vacuum bags within the chamber 404.

For both the flat bed lamination press and the autoclave lamination press, the 5 temperatures, pressures, and dwell times are in accordance with the need to laminate one or more layers of LCP dielectric material to other layers of material, as discussed *infra*. Thus during the lamination process, the LCP dielectric material should be laminated at a temperature T wholly in the liquid crystal temperature range (i.e., $T < T_{NL}$) with no excursion into the isotropic temperature range, under sufficient pressurization and for a sufficient dwell time to cause the 10 LCP dielectric material to be effectively laminated to the layer of material. For many applications, pressure in the range of 1000 to 3000 psi will effectuate good adhesion. The dwell time for maximum temperature and pressure should generally be at least 2 minutes, and applicable ranges of dwell times include, *inter alia*, 2 to 60 minutes and 15 to 30 minutes.

It is known in the art that for lamination of conventional thermoset dielectric layers (e.g. 15 epoxy/glass pre-preg), comparable results (e.g., with respect to adhesion and flow) can be obtained at reduced pressure in an autoclave versus a flat bed press. This suggests that in the case of LCP lamination, reduced pressures (perhaps by as much as a factor of two) may be effective, and thus desirable for reducing costs associated with autoclave lamination.

In addition to use of the flat bed lamination press and the autoclave lamination press for 20 laminating stacked LCP dielectric layers to other layers, other lamination press hardware known to one of ordinary skill in the art may be used for accomplishing such laminations in accordance

with the aforementioned conditions on temperature, pressure, and dwell time.

The lamination process can be used to stack layers of LCP dielectric material with layers of dielectric material (i.e., either LCP dielectric or non-LCP dielectric) or metallic layers, (e.g., signal planes, power planes, ground planes, etc.). With such stacking, attention should be given to achieving correct layer to layer alignment. Each copper clad dielectric core can have reference (fiducial) holes that are used for mechanical pins to provide layer to layer alignment. Both the photolithography steps to form circuit features and the lamination process can utilize these reference holes. Special tooling that includes plates with corresponding holes that accommodate the pins are used. The reference holes in the dielectric cores can be formed prior to and used as a reference for the photolithography steps, or alternately, they can be formed after the photolithography steps and then drilled in reference to the circuit features. This technique allows for calculation of the optimal location for the pin holes, given that some distortion or size change of the core may have occurred during the photolithography (especially for thin layers). A further alternative is to use a means of optical alignment, where the circuit features on the cores are detected, and then the layers are positioned and held in place for the lamination process, without using any pins.

FIGS. 6-15 depict steps in the formation of a circuitized layer and FIGS. 16-19 depict formation of a multilayered stack with Z-axis interconnections, in accordance with embodiments of the present invention.

FIG. 6 depicts an electrical structure **11** having a double-sided cladded laminate with continuous electrically conductive layers **16** and **18** respectively positioned on opposite surfaces

13 and 14 of a dielectric layer 12, in accordance with embodiments of the present invention. The dielectric layer 12 may comprise any type of dielectric material known to one of ordinary skill in the art (e.g., organic dielectric material; polyimide (e.g., KAPTON®, UPILEX®, etc.); ceramic dielectric material; woven or non-woven fiber (e.g., glass, aramid, etc.) reinforced resin sheet; 5 particulate filled fluoro-polymer; LCP dielectric material; or any of the other dielectric materials currently used as clad laminate materials in the printed wiring board (PWB) industry or base material in the flex circuit industry. The dielectric layer 12 should have sufficient mechanical integrity to support the conductive circuit features after they have been patterned and not suffer detrimental effects at the required joining temperatures. The dielectric layer 12 may be 10 optimized for other parameters such as electrical characteristics (e.g., dielectric constant and loss), mechanical properties, thermal properties, dimensional stability, etc.

The conductive layers 16 and 18 of FIG. 6 may each comprise any electrically conductive material that can be patterned, and is solderable or can have a solderable surface layer applied. Metals (e.g., copper) may be used in the conductive layers 16 and 18. Each of the conductive 15 layers layers 16 and 18 can be applied to the dielectric layer 12 by laminating a foil, physical vapor deposition (i.e., vacuum evaporation or sputtering), electroplating or electroless plating, chemical vapor deposition (CVD), or other means known to one of ordinary skill in the art. Alternatively, the dielectric layer 12 could be applied to a metal foil by such methods as screening, slot coating, curtain coating, doctor blading, roll coating, rod coating, spraying, etc. 20 Two particularly advantageous classes of starting materials for the electrical structure 11 are: 1) double sided, copper clad laminates, as commonly supplied to the PWB industry; and 2) copper

clad films, as commonly supplied to the flex circuit industry and as described *infra* in conjunction with FIG. 9. A double sided, copper clad laminate has the advantage of having a rough, high area, surface, which will eventually need to bond with the infused liquid resin in the embodiment of FIG. 20, after etching the laminated foil. Depending on the materials of the 5 dielectric layer 12 and conductive layers 16 and 18, it may be possible to purchase the electrical structure 11 of FIG. 6 (e.g., copper cladded LCP dielectric material). If the dielectric layer 12 comprises LCP dielectric material then one can laminate sheets of metal (e.g., copper) to the dielectric layer 12 by the methods disclosed *supra* in conjunction with FIGS. 1-5. Otherwise, the electrical structure 11 in FIG. 1 may be formed by any method known to one of ordinary skill in 10 the art.

FIG. 7 depicts the electrical structure 11 of FIG. 6 after a removable protective coating 20 (e.g., resist) has been applied to the electrically conductive layer 18 where electrically conductive circuitry will be subsequently formed, in accordance with embodiments of the present invention. The protective coating 20 will allow etching the conductive layer 16 so as to protect the cladding 15 of the conductive layer 18 from handling damage prior to circuit patterning, and act as a plating resist if dielectric via holes are to be filled with conductive material by a plating process. Use of the protective coating 20 is optional.

FIG. 8 depicts the electrical structure 11 of FIG. 7 after optional removal of the electrically conductive layer 16 which is not intended to be subsequently circuitized, in 20 accordance with embodiments of the present invention. The conductive layer 16 may be removed by any method known to a person of ordinary skill in the art such as by chemical

etching.

FIG. 9 depicts an electrical structure **21** having a single-sided cladded laminate with an electrically conductive layer **24** positioned on a surface **23** of a dielectric layer **22**, in accordance with embodiments of the present invention. The dielectric layer **22** may include any of the dielectric materials that may be comprised by the dielectric layer **12** of FIG. 6, discussed *supra*. The electrically conductive layer **24** may include any of the electrically conductive materials that may be comprised by the conductive layer **16** or **18** of FIG. 6, discussed *supra*. The conductive layer **24** may be applied to the dielectric by layer **22** by any method described *supra* in conjunction with FIG. 6 for applying the conductive layer **16** or **18** to dielectric layer **12** of FIG. 6. Depending on the materials of the dielectric layer **22** and conductive layer **24** and **18**, it may be possible to purchase the electrical structure **21** of FIG. 9 (e.g., copper cladded LCP dielectric material).

FIG. 10 depicts the electrical structure **21** of FIG. 9 after a removable protective coating **26** (e.g., resist) has been applied to the electrically conductive layer **24** where electrically conductive circuitry will be subsequently formed, in accordance with embodiments of the present invention. The protective coating **26** will protect the conductive layer **24** from handling damage prior to circuit patterning, and act as a plating resist if dielectric via holes are to be filled with conductive material by a plating process. Use of the protective coating **26** is optional and is analogous to the protective coating **20** of FIGS. 7-8. Note that the electrical structures **11** and **21** of FIGS. 8 and 10, respectively, are essentially the same electrical structures.

FIG. 11 depicts an electrical structure **10** derived from the electrical structure **11** of FIG. 8

(or, equivalently, the electrical structure **21** of FIG. 10) after formation of vias **31** and **32** in the dielectric layer **12**, in accordance with embodiments of the present invention. The vias **31** and **32** may be formed by any process known to one of ordinary skill in the art, such as laser drilling, plasma etching, etc.

5 FIG. 12 depicts the electrical structure **10** of FIG. 11 after the vias **31** and **32** have been filled with an electrically conductive filling material to form electrically conductive plugs **33** and **34**, respectively, in the vias **31** and **32**, in accordance with embodiments of the present invention. The exposed surface of the electrically conductive filling material should be even with, or slightly above the surface **15** of the dielectric layer **12** after filling the vias **31** and **32** to assure

10 good electrically conductive contact during subsequent joining with an external electrically circuitized layer as described *infra* in conjunction with FIG. 19. In FIG. 12, filling the vias **31** and **32** to form the conductive plugs **33** and **34** can be accomplished by any process known to one of ordinary skill in the art such as, *inter alia*, by a plating of metal (e.g., electroplating or electroless plating), or by forcing (e.g. by squeegeeing) electrically conductive paste into the vias and subsequently curing the paste. Having a continuous conductive layer on the circuit side of

15 the layer is particularly advantageous in the case of electroplating. In the case of conductive paste via fill, it may be desirable to modify the surface of the fill material to assure good solder bonding during the joining described *infra* in conjunction with FIG. 19. The conductive plugs **33** and **34** may each comprise any electrically conductive material that can be used to fill the vias **31**

20 and **32**, respectively.

FIG. 13 depicts the electrical structure **10** of FIG. 12 after electrically conductive caps **35**

and 36 have been formed on the electrically conductive plugs 33 and 34, respectively, in accordance with embodiments of the present invention. The conductive caps 35 and 36 may comprise a thin layer (e.g., 0.1 mils - 0.4 mils thickness) of tin or tin containing solder alloy. The conductive caps 35 and 36 may be formed with electroplating or electroless plating, both of which are maskless and self aligning for this process. Other solder alloys which are found to be compatible with fluxless soldering would be suitable replacements for tin containing solder alloys in these processes and structures. The conductive caps 35 and 36 may include any electrically conductive material that melts, and functions as a solder during subsequent joining of the electrical structure 10 with an external electrically circuitized layer as described *infra* in conjunction with FIG. 19.

FIG. 14 depicts the electrical structure 10 of FIG. 13 after removal of the protective layer 20, and after a photoresist 38 has been patterned, exposed, and developed after being applied to the conductive layer 18, in accordance with embodiments of the present invention. The patterning of the photoresist 38 is in accordance with the circuit pattern to be subsequently formed, as described *infra* in conjunction with FIG. 15.

FIG. 15 depicts the electrical structure 10 of FIG. 14 after the conductive layer 18 (e.g., copper foil) has been circuitized to form the circuitization 39 in accordance with the photoresist pattern of the photoresist 38 (see FIG. 14), and after the photoresist 38 has been removed such that the electrical structure 10 has become a circuitized layer, in accordance with embodiments of the present invention.

FIG. 16 depicts the electrical structure 10 (i.e., circuitized layer) of FIG. 15 immersed in a

plating solution **42** (e.g., a tin plating solution) within a container **40**, in accordance with 5 embodiments of the present invention. Said immersion of the electrical structure **10** in the plating solution **42** is optional and may enhance wetting, and thus yields, at joining of the electrical structure **10** with an external electrically circuitized layer as described *infra* in conjunction with FIG. 19. With a tin plating solution, formation of a tin oxide on the surface of the circuitization **39** (e.g., copper circuitry) may provide better adhesion of the infused resin to the circuitry than the native copper oxide in the resin infusion embodiment discussed *infra* in conjunction with FIG. 20.

FIG. 17 depicts the electrical structure **10** (i.e., circuitized layer) of FIG. 15 being treated 10 with a plasma (e.g., a fluorinated plasma gas) in a plasma reaction chamber **44**, in accordance with embodiments of the present invention. In FIG. 17, the plasma reaction generates fluorine ions **46** which interact with metal surfaces (e.g., tin, copper, etc) of the conductive caps **35** and **36** and the circuitization **39** to form fluorides or oxifluorides (e.g., tin oxifluoride). This plasma treatment improves wetting of the metal surfaces so that subsequent soldering may be 15 effectuated, as described *infra* in conjunction with FIG. 19, without the need for a fluxing agent during the solder reflow and joining step of FIG. 19. Such use of a fluorinated plasma gas is described in: United States Patent 4,921,157 to Dishon et al. 1990 (incorporated herein by reference in its entirety); United States Patent 5,407,121 to Koopman et al. 1995 (incorporated herein by reference in its entirety); and United States Patent 5,776,551 to Pasch 1998 20 (incorporated herein by reference in its entirety).

FIG. 18 depicts circuitized layers **50**, **60**, and **70** stacked and aligned to form a

multilayered stack **48** with Z-axis interconnections (which will be defined *infra* in conjunction with FIG. 19), in accordance with embodiments of the present invention. The circuitized layer **50** comprises an electrical circuitization **59** on a surface **51** of dielectric layer **52**. Electrically conductive plugs **53** and **54** are electrically and mechanically connected to the electrical circuitization **59** and are respectively capped with electrically conductive caps **55** and **56**. The circuitized layer **60** comprises an electrical circuitization **69** on a surface **61** of dielectric layer **62**. Electrically conductive plug **64** is electrically and mechanically connected to the electrical circuitization **69** and is capped with electrically conductive cap **66**. The circuitized layer **70** comprises an electrical circuitization **79** on a surface **71** of dielectric layer **72**. Electrically conductive plugs **73** and **74** are electrically and mechanically connected to the electrical circuitization **79** and are respectively capped with electrically conductive caps **75** and **76**. For many applications, standard alignment methods, such as slots over pins, will provide adequate registration of the circuitized layers **50**, **60**, and **70**. For very dense structures with critical registration tolerances, optical alignment of adjacent layers may be required. In either case, it is possible to reduce alignment shifts during mass joining by tack soldering a few joints per square inch as each new circuitized layer is added to the multilayered stack **48**. Tack soldering can be accomplished by pressing over the joint location with a hot probe (e.g., a fine tipped soldering iron) from the circuit side of the circuitized layer (for better heat transfer).

FIG. 19 depicts the multilayered stack **48** of FIG. 18 after the circuitizations on adjacent circuitized layers have been electrically joined through conductive plugs by soldering (“solder joining”) using the relevant interfacing conductive caps as solder, which forms the void volumes

81-86 in the multilayered stack 48, in accordance with embodiments of the present invention.

For example, the circuitization 59 of circuitized layer 50 is electrically joined to the circuitization

69 of circuitized layer 60 by the conductive plug 64 of the circuitized layer 60 using the

conductive cap 66 as solder. As another example, the circuitization 69 of circuitized layer 60 is

5 electrically joined to the circuitization 79 of circuitized layer 70 by the conductive plug 74 of the circuitized layer 70 using the conductive cap 76 as solder. Note that the conductive plugs 64 and

74 of adjacent circuitized layers 60 and 70 are both oriented in the layer thickness direction 88,

and are offset with respect to each other in the direction 89 that is perpendicular or about

perpendicular to the layer thickness direction 88. Alternatively, the conductive plugs 64 and 74

10 may be positioned so as not to be offset with respect to each other in the direction 89. In the

preceding examples, the conductive plug 64 forms a “Z-axis” interconnection between the

circuitized layers 50 and 60, wherein the conductive plug 64 mechanically and electrically

connects the circuitizations 59 and 69 with each other. The “Z-axis” is an axis in the direction

88. Similarly, the conductive plug 74 forms a “Z-axis” interconnection between the circuitized

15 layers 60 and 70, wherein the conductive plug 74 mechanically and electrically connects the

circuitizations 69 and 79 with each other.

Use of the Z-axis interconnections eliminates the need for plated through holes to make

layer to layer electrical connections. Instead, electrical connections are made from one layer to

another by forming chains or stacks of solder connections between pads. This is more compact

20 and space efficient than plated through holes. With the present invention, individual layers are

formed in parallel and then aligned and joined which results in a substantial reduction in

fabrication time as compared with the conventional sequential build-up micro-via technologies.

In FIG. 19, joining of the circuitized layers **50**, **60**, and **70** (i.e., “mass joining”) is accomplished by heating the circuitized layers **50**, **60**, and **70** to a temperature that exceeds the melting point of the solder which caps the filled vias (i.e., the melting temperature of the electrically conductive caps **55**, **56**, **66**, **75**, and **76**). Heating can be performed in a batch or conveyorized oven, or between heated platens. Light pressure, applied by parallel plates above and below the multilayered stack **48**, is all that is needed to provide joint contact for joining. Pressure beyond that required to insure contact of surfaces to be joined is not needed or desirable. A traditional laminating press is not required. The joining atmosphere can be ambient, inert (e.g. nitrogen), or vacuum. Application of a vacuum at some point while at joining temperatures may improve the escape of any materials volatilized during the joining process. As stated *supra*, the joining process is performed fluxlessly; i.e., without the need for a fluxing agent during the solder reflow and joining step.

FIG. 20 depicts the multilayered stack **48** of FIG. 19 after a resin **90** (e.g., a low viscosity, thermosetting resin) has been infused into the void volumes **81-86** and subsequently cured. Said infusion of resin **90** may be achieved by a process known as vacuum bagging. A gas impermeable, flexible covering is placed around the multilayered stack **48**, and sealed around the top and bottom periphery of the multilayered stack **48**. A series of (generally opposed) vacuum and resin supply ports are placed around the edges of the joined structure. The atmosphere within the flexible covering is evacuated, through the vacuum port(s), by means of a vacuum pump, and the resin is allowed to flow into the area within the flexible covering through the resin

port(s). Surface tension and atmospheric pressure pushing on the resin supply cause the resin to flow into all of the void volumes **81-86**. The resin is then thermally cured, resulting in a monolithic structure.

In FIG. 20, some or all of the electrically conductive plugs **53, 54, 64, 73, and 74** may 5 be parallel or about parallel to each other, and oriented in the direction **88** or approximately in the direction **88**. Some or all of the electrically conductive plugs **53, 54, 64, 73, and 74** may be offset from each other in the direction **89** that is perpendicular or about perpendicular to the direction **88**.

After infusion of resin **90**, it may not be necessary to form a through hole through the 10 multilayered stack **48**; however, the present invention permits forming a through hole through the multilayered stack **48** after infusion of resin **90**.

FIG. 21 depicts the multilayered stack **48** of FIG. 19 with the dielectric layers **52, 62, and 72** each comprising a liquid crystal polymer (LCP) material and after high pressure has been applied to the multilayered stack **48** to fill the void volumes **81-86** with the LCP material and 15 bond dielectric layers of adjacent circuitized layers with each other (i.e., dielectric layers **52** with dielectric layer **62**; and dielectric layer **62** with dielectric layer **72**), in accordance with embodiments of the present invention. Referring to FIG. 19, the void volumes **81** and **82** are respectively filled with LCP material from at least one of the LCP dielectric layers **52** and **62**. The void volumes **83** and **84** are respectively filled with LCP material from at least one of the 20 LCP dielectric layers **62** and **72**. The void volumes **85** and **86** are filled with LCP material from LCP dielectric layer **72** and from any other LCP dielectric layer that is adjacent to void volumes

85 and 86. In FIG. 21, the dielectric layers 52, 62, and 72 of FIG. 19 each comprise the same LCP material 95. Generally, the dielectric layers 52, 62, and 72 may each comprise a same dielectric LCP material or different LCP dielectric materials

In FIG. 21, some or all of the electrically conductive plugs 53, 54, 64, 73, and 74 may 5 be parallel or about parallel to each other, and oriented in the direction 88 or approximately in the direction 88. Some or all of the electrically conductive plugs 53, 54, 64, 73, and 74 may be offset from each other in the direction 89 that is perpendicular or about perpendicular to the direction 88.

The multilayered stack 48 in FIG. 21 has been laminated together by any of the methods 10 discussed *supra* in conjunction with FIGS. 1-5 for bonding LCP material to adjacent layers. In particular, the lamination temperature T is to be wholly in the liquid crystal temperature range (i.e., $T < T_{NI}$) of the LCP dielectric material of dielectric layers 52, 62, and 72 with no excursion into the isotropic temperature range, under sufficient pressurization (e.g., 1000 to 3000 psi) and for a sufficient dwell time to cause the LCP dielectric material of dielectric layers 52, 62, and 72 15 to plastically deform such that: 1) the dielectric layer 62 is directly bonded to the dielectric layer 52 with no extrinsic adhesive material disposed between the dielectric layer 62 and the dielectric layer 52; 2) the dielectric layer 62 is directly bonded to the circuitization 59 with no extrinsic adhesive material disposed between the dielectric layer 62 and the circuitization 59; 3) the dielectric layer 72 is directly bonded to the dielectric layer 62 with no extrinsic adhesive material 20 disposed between the dielectric layer 72 and the dielectric layer 62; and 4) the dielectric layer 72 is directly bonded to the circuitization 69 with no extrinsic adhesive material disposed between

the dielectric layer 72 and the circuitization 69. The dwell time for maximum temperature and pressure should generally be at least 2 minutes, and applicable ranges of dwell times include, *inter alia*, 2 to 60 minutes and 15 to 30 minutes. FIG. 22 shows that said lamination process caused the void volumes 81-86 to be filled with the LCP dielectric material of dielectric layers 52, 62, and 72. If multiple LCP dielectric materials are used in the dielectric layers 52, 62, and 72, then the value of T_{NI} to be employed for satisfying $T < T_{NI}$ is the lowest value of T_{NI} of all such LCP dielectric materials included within the dielectric layers 52, 62, and 72. The polymer chain structure and associated directional orientation of the LCP dielectric material of dielectric layers 52, 62, and 72 remains essentially unchanged throughout the dwell time. Similarly, the coefficient of thermal expansion (CTE) of the LCP dielectric material of dielectric layers 52, 62, and 72 remains essentially unchanged throughout the dwell time. The use of the LCP material in the dielectric layers 52, 62, and 72 avoids the resin infusion step described *supra* in conjunction with FIG. 20.

Formation of the multilayered stack 48 of FIG. 21, with dielectric layers 52, 62, and 72 each comprising a LCP material, has been described *supra* as comprising solder joining step (shown in FIG. 19) and a dielectric lamination step (shown in FIG. 21). In an alternative embodiment, the solder joining of FIG. 19 and the dielectric lamination of FIG. 21 can be performed simultaneously in a single step. In the alternative embodiment, the multilayered stack 48 of FIG. 18 is laminated together as described *supra* in conjunction with FIG. 21, subject to an additional constraint. The additional constraint is that the lamination temperature used for the dielectric lamination exceeds the melting point of the solder which caps the filled vias (i.e., the

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melting temperature of the electrically conductive caps **55, 56, 66, 75, and 76**), so as to effectuate the same solder joining that is shown in FIG. 19.

The interconnect structure of the multilayered stack **48** may be complete at this time, or optionally, the interconnect structure may be drilled, plated and circuitized (using standard 5 printed wiring board (PWB) processes) to allow mounting of pin-in-hole components. Mounting holes may be drilled and the interconnect structure may be used as a core/subcomposite in a higher level laminated interconnect structure, etc. After laminating together the multilayered stack **48** of FIG. 21, it may not be necessary to form a through hole through the multilayered stack **48**; however, the present invention permits forming a through hole through the 10 multilayered stack **48** after laminating together the multilayered stack **48** of FIG. 21.

The finishing operations are similar to those for traditional PWB's: application of a solder mask, modifying the surface finish (organic solder preservative, Ni/Au plating, solder coating, etc.), testing, machining to final outline, etc. Any of these finishing operations can be applied as needed, with the same wide variety of sequences as applicable to ordinary PWB's.

15 The multilayered stack **48** of the present invention can be used for, *inter alia*, the following types of applications: integrated circuit package substrates (e.g., chip carriers); PWB's for mounting and interconnecting a wide array of components that make up electronic products; and high density interconnect "patches" or appliqués, which can be joined to lower density interconnect structures (e.g. traditional PWB's) using the same joining methods employed in 20 fabricating the multi-layer patch, which provides for a localized area of high density interconnect where needed, without forcing the entire structure to be built at the premium costs required for

the high density area.

While embodiments of the present invention have been described herein for purposes of illustration, many modifications and changes will become apparent to those skilled in the art. Accordingly, the appended claims are intended to encompass all such modifications and changes as fall within the true spirit and scope of this invention.